TECHNICAL NOTE

D-67

BLOWOFF OF PROPANE AND HYDROGEN DIFFUSION FLAMES AT HIGH MACH NUMBER, RAMJET CONDITIONS

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SUMMARY

An investigation was made of the blowoff of hydrogen and propane diffusion flames stabilized in the wake of cylindrical fuel injectors at ramjet burner inlet conditions. The effect of varying pressure, temperature, and air and fuel flows was determined for several fuel-orifice tube sizes.

The propane blowoff data were correlated as $d_o^{0.7}p^{0.9}T_a^{1.2}w_f^{-0.5}$ as a function of U_a for 0.188- and 0.25-inch-diameter tubes. The hydrogen data were correlated as $T_a^{1.2}U_a^{0.2}$ as a function of pressure for various fuel flows and orifice diameters. The correlations were derived from a thermal ignition model for flame stabilization.

INTRODUCTION

Ramjets operating at Mach numbers in excess of 3 will have combustor inlet temperatures high enough to allow spontaneous ignition of the fuel without the need for conventional flameholders. Under these operating conditions, the fuel will burn as a diffusion flame stabilized at the fuel injector. Although much work has been done on the stability of premixed flames, little experimental work is available on the blowoff of diffusion flames. Scholefield and Garside (ref. 1) present 'lift' and blowoff velocities for ethylene diffusion flames in still air. Spalding's investigation of extinguishing diffusion flames burning from liquid droplets (refs. 2 and 3) proposes a reaction-rate theory for blowoff similar to that of Zeldovich (ref. 4). Potter and Butler (ref. 5) indicate that extinction of opposing jets of fuel and oxidant is a function of a critical mass flow of reactants into the flame.

The present investigation was carried out to determine the conditions that affect blowoff of propane and hydrogen diffusion flames stabilized in the wake of a cylindrical fuel injector. The range of operating conditions is given by the following table:

	Hydrogen	Propane
Air inlet temperature, $^{\circ}R$	1000-1900	1660-2160
Static pressure, atm	0.23-1.05	0.52-1.91
Air velocity, ft/sec	130-570	110-540
Fuel flow, lb/hr	0.525-3.48	0.525-3.78
Orifice diameter, in.	0.029-0.082	0.029-0.082
Fuel-injector diameter, in.	0.25	0.1875-0.312

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SYMBOLS

c_p heat capacity of mixture, Btu/(lb)($^{\circ}R$)

d diameter, in.

G mass velocity, lb/(sec)(sq ft)

p pressure, atm or lb/sq in.

q heat-transfer rate, Btu/hr

Re Reynolds number

T static temperature, $^{\circ}R$

U flow velocity, ft/sec

u burning velocity, ft/sec

w flow rate, lb/hr

x distance along a streamline, in.

δ_m thickness of prereaction zone, in.

ϵ eddy diffusivity, sq ft/sec

$\varkappa$ thermal conductivity, (Btu/(hr)(sq ft))($^{\circ}F$/ft)

μ viscosity, lb/(ft)(sec)

ρ density, lb/cu ft

τ ignition lag, sec

φ function

Subscripts:

a air

bo blowoff

F flame

f fuel

i ignition

j jet

o orifice

r required

t tube

v vortex

0 initial mixture conditions

APPARATUS

The apparatus is shown schematically in figure 1. Air and exhaust were supplied from the laboratory systems and controlled by remotely operated valves. The air was heated by passing it through 5/8-inch-O.D. Inconel tubes forming the three legs of a Y-circuit resistance heater. The air entered a 2- by 4-inch Inconel duct through a manifold. Straightening was accomplished with a tube bundle 6 inches upstream of the test section, and turbulence was reduced with three small-mesh screens. The test section consisted of a 2- by 1-inch convergent nozzle expanding abruptly to the 2- by 4-inch duct. The fuel injectors, which were located immediately downstream of the nozzle in the potential core of the jet, consisted of 0.188-, 0.25-, and 0.312-inch-diameter Inconel tubes with a single orifice facing downstream. Quartz windows 3 inches in diameter were located on both sides of the test section. One of these windows was replaced with a plate containing a retractable spark ignitor for the propane runs. The duct was covered with 4-inch-thick insulation.

Air and fuel flows were metered with calibrated rotameters. Static pressure downstream of the nozzle was measured with a mercury manometer. Air total temperature was measured upstream of the nozzle by a Chromel-Alumel sonic-aspirated thermocouple.

PROCEDURE

For hydrogen, air inlet temperatures were high enough for spontaneous ignition of the fuel. The propane jets were ignited with a sparkplug that was retracted following ignition.

All blowoffs were effected by slowly decreasing the burner pressure at intervals of air temperature, airflow, and fuel flow. This proved to be the most precise method, since pressure was independently controllable. All other variables were varied independently of one another. For the 0.188- and 0.312-inch-diameter fuel injectors, data were taken to determine the effect of tube size. Airflow and temperature for these runs were held substantially constant, and blowoff pressure was determined as a function of fuel flow.

At high pressures with the large fuel orifices, the pressure at blowoff became less reproducible, in that intermittent flame separation and flashback occurred. For these cases, blowoff data were recorded at the pressure where the flames no longer flashed back to the injector. Where blowoff and blowout were simultaneous (no downstream burning), burner pressure was taken just before blowoff.

RESULTS

Typical blowoff data for propane and hydrogen diffusion flames are plotted in figures 2 to 4.

Effect of Air Velocity

Figure 2 shows the effect of air velocity on blowoff pressure for propane and hydrogen, where fuel flow and inlet air temperature are held constant for each curve. In general, the effect of a variation in air velocity on blowoff pressure is small. The effect of increasing the air velocity is usually stabilizing, although variable with orifice size and fuel flow. For some cases, a slight destabilizing effect is produced.

Effect of Inlet Air Temperature

Figure 3 shows the effect of inlet air temperature on blowoff pressure for various orifice sizes. Airflow and fuel-flow rates are held constant. Blowoff pressure decreases as the air temperature is raised.

Effect of Fuel-Flow Rate

Figure 4 indicates the effect of varying fuel flow on blowoff pressure while airflow rate and temperature are held constant. The results are plotted as fuel Reynolds number against blowoff pressure with airflow and orifice diameter as the parameters. The fuel was heated by the airstream in passing through the tube, and its temperature varied with flow rate. Orifice diameter is used arbitrarily as the length in Re_f. As expected (e.g., ref. 1), increases in fuel flow result in decreased stability. The breaks in the curves appear at a constant Re_f, with the exception of the 0.082-inch orifice, where the range does not extend to the lower fuel flows. The smaller effect of fuel flow on blowoff for hydrogen (with the exception of the 0.082-inch orifice) may be due to choking of the fuel jet throughout the flow range.

Effect of Orifice Size

At approximately equal fuel mass velocities, there appears to be an orifice size for which blowoff pressure is a minimum. The effect is shown in figure 5 for hydrogen, where all variables except blowoff pressure are held constant.

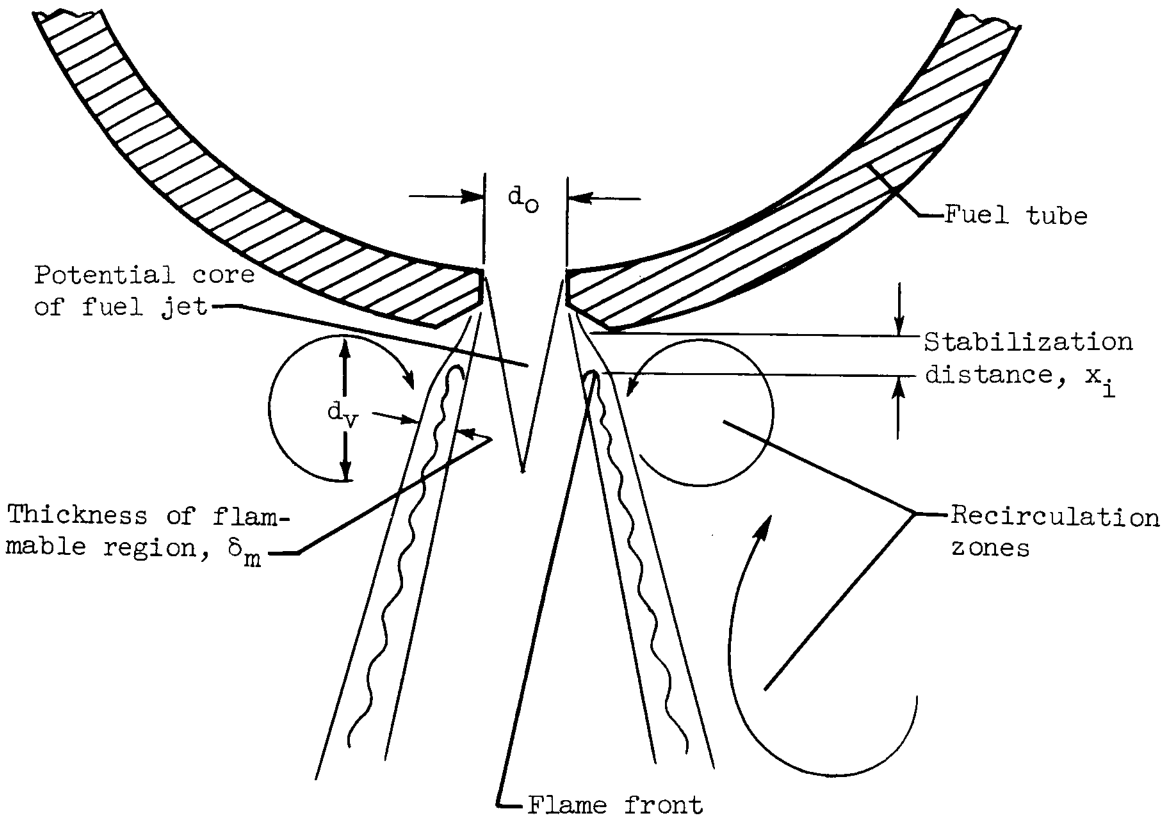
Photographs of the hydrogen flames taken from motion-picture film as the pressure was reduced are shown in figure 6. The transition to a laminar flame is suggested by the changed flame spreading angle at lower pressures.

Photographs of the propane flames are shown in figure 7. Figure 7(a) is a time exposure of a typical turbulent propane flame. Exposures at 1/1000 second are shown in figure 7(b). These indicate periodic fluctuations of the flame that may be due to eddy-shedding from the cylinder.

ANALYSIS

Although the shape and length of diffusion flames can be calculated from aerodynamic mixing considerations alone, the lifting or blowoff of these flames must be determined by a combination of limiting reaction kinetics and aerodynamic effects. In this case, some of the considerations that apply for stability of premixed flames must apply for diffusion flames.

The following sketch indicates the position of the flame front near the stabilization position for a fuel jet in the wake of a cylinder:



For stabilization to occur near the orifice, the mixture flow velocity must not exceed the burning rate. The recirculation zone in the wake of the cylinder and at the base of the fuel jet provides the low-velocity region for stabilization. The extreme curvature of the flame front at the base indicates the variation of burning rate with concentration in the mixing zone.

The flame can approach the orifice no closer than a distance that depends on an ignition delay and on heat losses from the preignition region. The pressure or inlet-temperature dependence of the flame speed is small compared with the dependence on pressure and inlet temperature of the distance determined by the ignition lag and quenching (refs. 6 and 7). For the flame to blow off, the flame front must be displaced until it reaches a critical position where the flow velocity exceeds the burning rate at every point. Thus, small changes in flame speed will not determine blowoff.

All experimental data were correlated by an equation relating the energy required for thermal ignition to the heat transferred from the flame front to the jet by the recirculating air. The flame at the stabilization point was always assumed to be laminar.

The energy required to heat the incoming mixture to the ignition temperature is given for a turbulent jet by the following expression:

$$q_r \propto \delta_m d_j \rho c_p u(T_i - T_0) \tag{1}$$

where u is the laminar flame speed, which is equal to the mixture velocity at the stabilization point.

The thickness of the flammable mixing region δ_m is assumed proportional to ϵ/U_f, where ϵ is the eddy diffusivity in the recirculation zones and U_f is the mean fuel velocity in the mixing region.

Equation (1) can be rewritten as

$$q_r \propto (\epsilon/U_f) d_j \rho c_p u(T_i - T_0) \tag{2}$$

The heat transferred from the vortex at the base of the fuel jet to the preignition zones is

$$q_t \propto \left[\left(\frac{d_v \rho_a U_a}{\mu_a}\right)^{0.8} \frac{\varkappa}{d_v}\right] d_j x_i (T_F - T_0) \tag{3}$$

The Reynolds number exponent has been taken as 0.8 for flow parallel to a cylinder, the cylinder being the approximate shape of the column of flammable mixture. The heat-transfer area was assumed proportional to the product of the jet diameter and a distance x_i, the distance from the orifice to the flame base. The length in Re is related to the diameter of the vortex at the base of the fuel jet.

At blowoff the heat required for ignition is infinitesimally greater than the heat supplied from the recirculation zone. Equating equations (2) and (3) and combining terms give

$$\varphi_0(U_f) = \left(\frac{\varkappa}{\rho c_p \epsilon}\right) \frac{\rho^{0.8} U_a^{0.8}}{\mu_a^{0.8} d_v^{0.2}} \frac{x_i}{u} \frac{T_F - T_0}{T_i - T_0} \tag{4}$$

Assuming $\mu \propto \sqrt{T}$ and substituting for ρ,

$$\varphi_1(U_f) = \left(\frac{\varkappa}{\rho c_p \epsilon}\right) \frac{p^{0.8} U_a^{0.8}}{d_v^{0.2} T_a^{1.2}} \left(\frac{x_i}{u}\right)\left(\frac{T_F - T_0}{T_i - T_0}\right) \tag{5}$$

The eddy diffusivity can be taken as proportional to the air velocity (at distances close to the orifice) and to the fuel tube diameter, $\epsilon \propto U_a d_t$. For turbulent mixing, the pressure and temperature dependence of the thermal diffusivity can be neglected, so that equation (5) becomes

$$\varphi_2(U_f) = \frac{p^{0.8}}{U_a^{0.2} T_a^{1.2} d_t d_v^{0.2}} \left(\frac{x_i}{u}\right)\left(\frac{T_F - T_0}{T_i - T_0}\right) \qquad (6)$$

The term (x_i/u) has the dimensions of time and can be thought of as an ignition lag τ. The lag varies exponentially with the ignition temperature T_i. If this is assumed to be close to the flame temperature, the last term will be constant and about equal to unity.

Correlation of Propane Data

Since most of the propane flames appeared turbulent, a correlation was attempted with equation (6). The dependence of ignition delay on pressure was taken from ethane data (ref. 7) as $\tau \propto p^{-1.7}$. Flame temperatures were computed for the extreme range of inlet temperature and blowoff pressures for hydrogen. The resulting change in τ was only 8 percent, assuming that $T_i = T_F$. The variation of flame temperature for propane was even less. Hence, the temperature dependence of τ was neglected. The air temperature variation was not sufficient for an empirical verification of the temperature exponent, and a value somewhat higher than the predicted value of 1.2 may be indicated. The dependence of the right side of equation (6) on fuel flow was determined empirically as $w_f^{-0.5}$, since the relation of U_f and w_f was not known. The flow conditions in the cylinder wake are complicated by the presence of recirculation zones and by the fact that fuel flow was choked over a part of the flow range. Moreover, the turbulent diffusion coefficient in the mixing zone may be somewhat dependent on the jet velocity. The propane data were plotted showing the blowoff parameter $p^{0.9}T_a^{1.2}w_f^{-0.5}$ as a function of air velocity U_a. The data for the 0.25-inch-diameter tube are shown in figure 8(a). The effect of air velocity is small except at the lower air velocities. The minimum indicated for several of the curves represents a variation of the velocity exponent from about -0.35 to 0.1.

Figures 8(b) and (c) are plots of the parameter for the 0.188- and 0.312-inch-diameter tubes, respectively. Air temperature and flow rate are constant. Each curve represents the blowoff conditions for a particular orifice. Conditions for stable burning exist above the curves.

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Increasing pressure and temperature result in more stable conditions at the same fuel flow and air velocity. Increasing the fuel-flow rate results in a large increase in blowoff pressure, so that the net result is an increase in the parameter.

The effect of orifice diameter was determined empirically from figure 8(a) as $p^{0.9}T_a^{1.2}w_f^{-0.5} \propto d_o^{-0.7}$, whereas equation (5) indicates proportionality of the parameter to $d_t d_v^{-0.2}$. The data of figures 8(a) and (b) are replotted in figure 8(d) as $d_o^{0.7}p^{0.9}T_a^{1.2}w_f^{-0.5}$ against air velocity. The data for the 0.312-inch-diameter tube showed considerable scatter and are not included.

Correlation of Hydrogen Data

The hydrogen flames appeared completely turbulent only at higher pressures. As pressure was decreased, a transition from turbulent to laminar flow occurred in the flame front, as is shown by the photographs (fig. 6). The hydrogen blowoff data did not correlate with a constant pressure exponent. Therefore, the results are plotted in figure 9 as $T_a^{1.2}U_a^{0.2}$ against pressure for each fuel-orifice size and fuel flow.

An explanation of the varying pressure exponent is given by the results of reference 7, where ignition lag for hydrogen is shown as a function of pressure. A maximum ignition lag occurs at approximately 0.5 atmosphere. Below 0.5 atmosphere, the ignition lag decreases with decreasing pressure.

In figures 9(a), (b), and (d), the slopes of all curves tend to approach a constant value of about -0.1, at a pressure below 0.5 atmosphere.

Since transition to a laminar flame occurs at low pressures, changes in thermal diffusivity can no longer be neglected in equation (5). Since ignition lag in the lower pressure range is decreasing with decreasing pressure, the ignition distance will no longer be limiting for blowoff. Rewriting equation (5) gives

$$\varphi_3(U_f) \propto \left(\frac{\kappa}{\rho c_p u}\right) \frac{p^{0.8}}{d_t d_v^{0.2} U_a^{0.2} T_a^{1.2}} \frac{T_F - T_0}{T_i - T_0} \qquad (7)$$

Thermal diffusivity divided by the laminar flame speed is proportional to the thickness of the preignition zone. This might be thought of as a maximum thickness normal to the stabilization point that allows a stable flame. The pressure dependence of this term will be $p^{-0.9}$, since

$\varkappa/\rho c_p \propto p^{-1}$ and $u \propto p^{-0.1}$. The over-all pressure exponent of -0.1 in equation (7) compares favorably with the results. The inlet temperature dependence of the thermal diffusivity cancels the temperature dependence of the flame speed, if changes in flame temperature are neglected (ref. 6).

Comparison of Hydrogen and Propane Stability

A direct comparison of the hydrogen and propane stability parameters is difficult because of the varying pressure exponent for hydrogen and a somewhat lower dependence on fuel flow. An approximate comparison was made, however, by comparing the hydrogen data with propane using the parameter $p^{0.9}T_a^{1.2}w_f^{-0.5}$ at pressures where the pressure exponent was approximately 0.9 and for the same orifice diameter. The results indicated that the hydrogen flames were more stable by a factor of 1.6 to 3. This is in good agreement with the ratio of flame speeds for stoichiometric hydrogen-air and propane-air (refs. 8 and 9), for the appropriate temperature range of this investigation.

SUMMARY OF RESULTS

An investigation of the stability of hydrogen and propane diffusion flames in the wake of a cylindrical fuel injector yielded the following results:

1. The blowoff of the propane diffusion flames was correlated as $d_o^{0.7}p^{0.9}T_a^{1.2}w_f^{-0.5}$ as a function of air velocity for 0.188- and 0.25-inch tube diameters.

2. The blowoff of hydrogen flames was partially correlated as $T_a^{1.2}U_a^{0.2}$ as a function of pressure for constant values of fuel flow and orifice diameter.

3. Increases in air temperature had a marked effect in increasing the stability of the flames.

4. The effect of increasing fuel flow was found to be strongly destabilizing except for hydrogen flame blowoff at low pressures, which was insensitive to changes in fuel flow.

5. At equal fuel mass velocities, there appeared to be an optimum orifice size of 0.040 to 0.050 inch, but for equal fuel flows, the propane correlation showed increasing stability with orifice size. The hydrogen data on the same basis appeared less sensitive to orifice diameter.

6. The ratio of stabilities of the two fuels was roughly equal to the ratio of their flame speeds at high inlet temperatures.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 26, 1959

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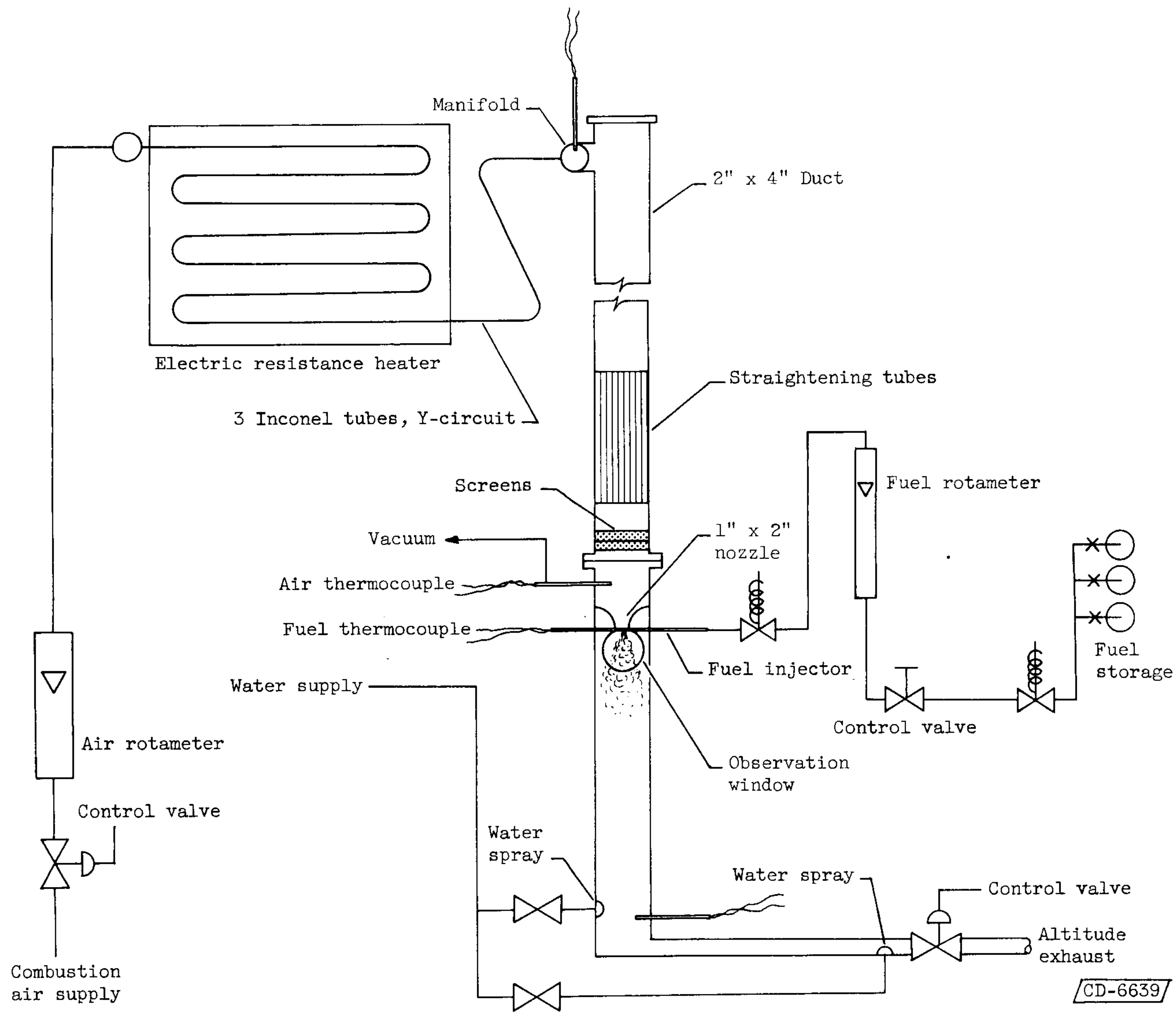
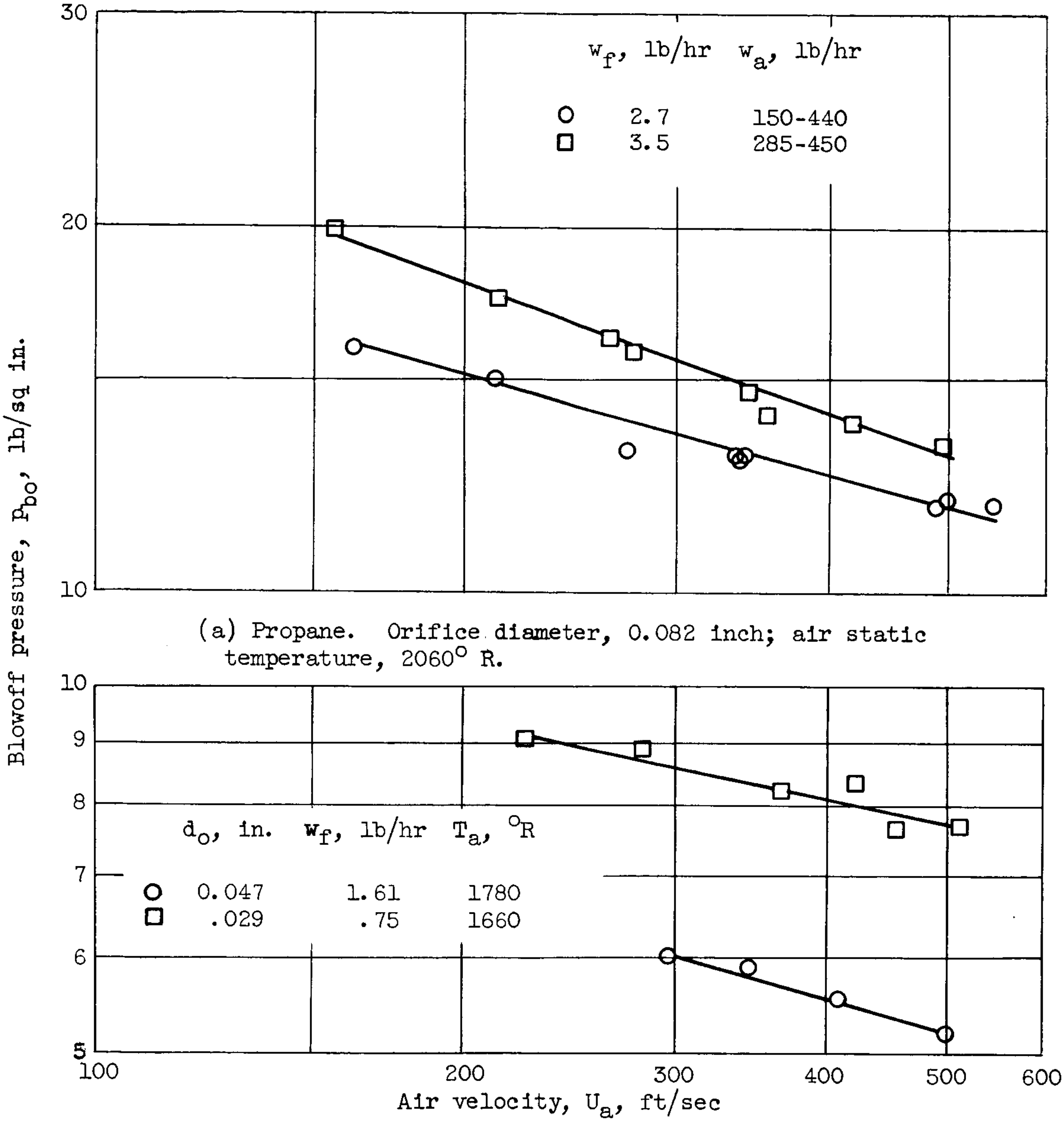


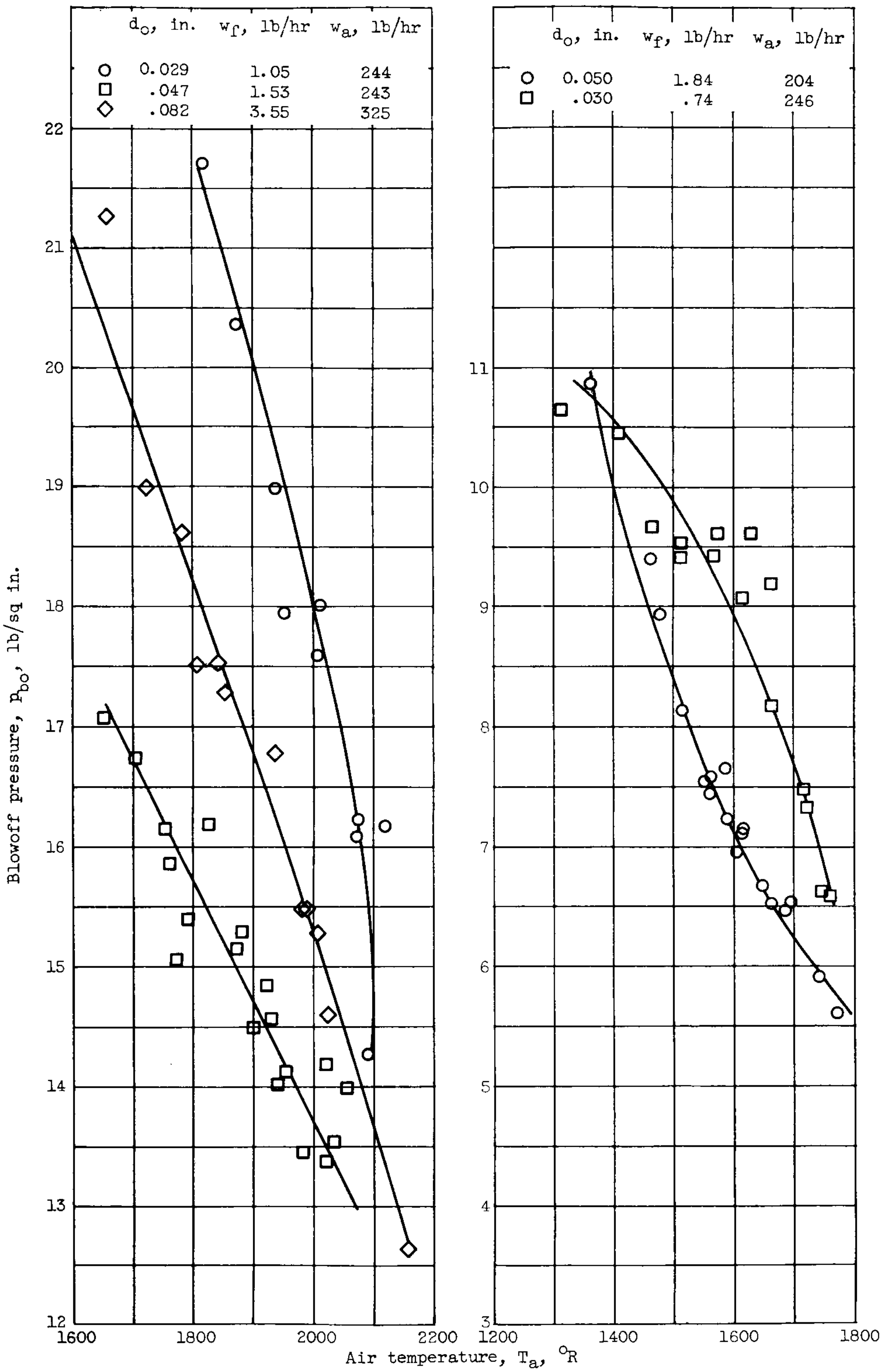
Figure 1. - Schematic diagram of test apparatus.



(a) Propane. Orifice diameter, 0.082 inch; air static temperature, 2060° R.

(b) Hydrogen.

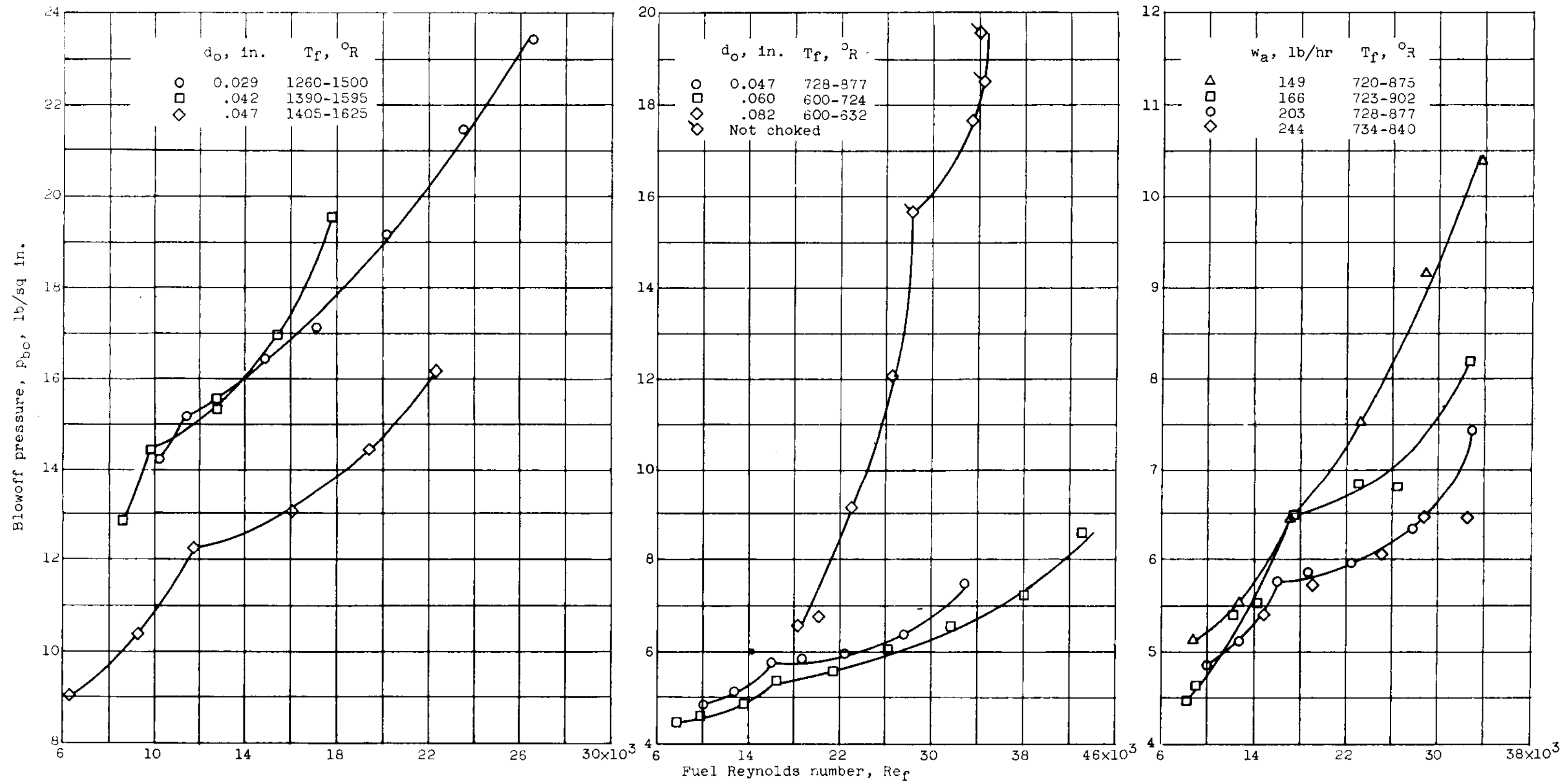
Figure 2. - Effect of air velocity on blowoff pressure.



(a) Propane.

(b) Hydrogen.

Figure 3. - Effect of inlet air temperature on blowoff of diffusion flames.



(a) Propane. Air static temperature, 2060° R; airflow, 242 pounds per hour.

(b) Hydrogen. Air static temperature, 1660° R; airflow, 204 pounds per hour.

(c) Hydrogen. Orifice diameter, 0.047 inch; air static temperature, 1660° R.

Figure 4. - Effect of fuel Reynolds number on blowoff pressure of diffusion flames.

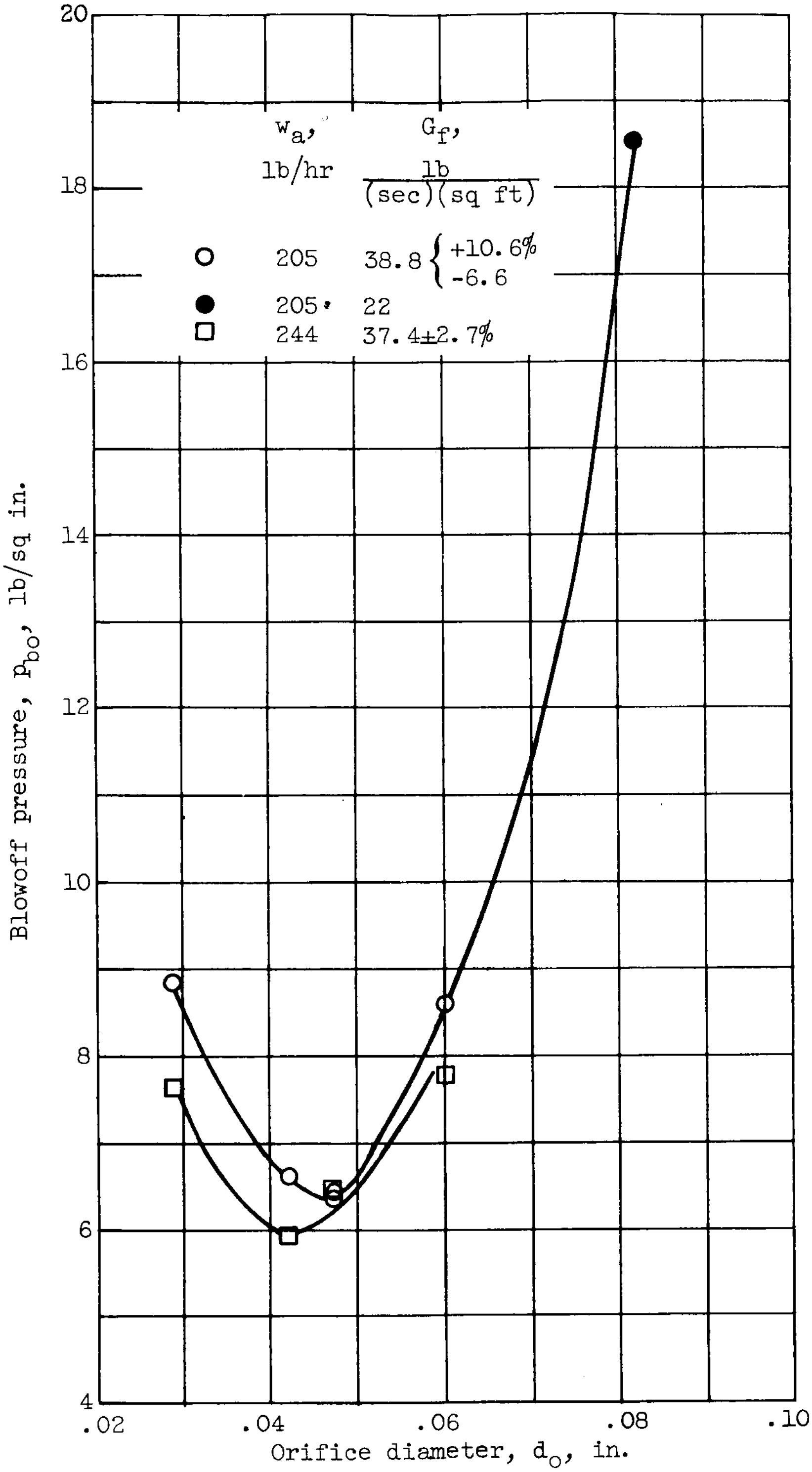


Figure 5. - Effect of orifice diameter on blowoff pressure of hydrogen diffusion flames. Air static temperature, 1660° R.

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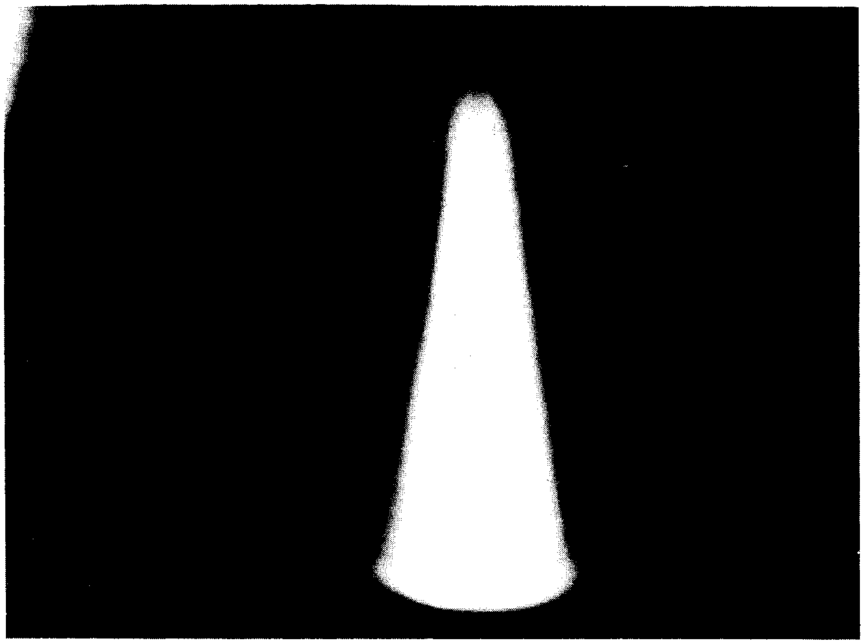
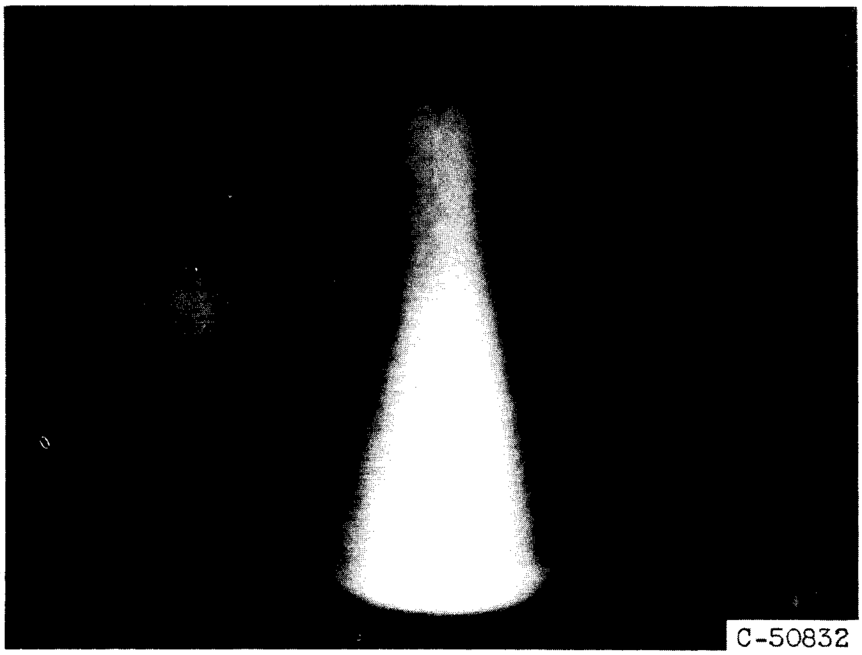
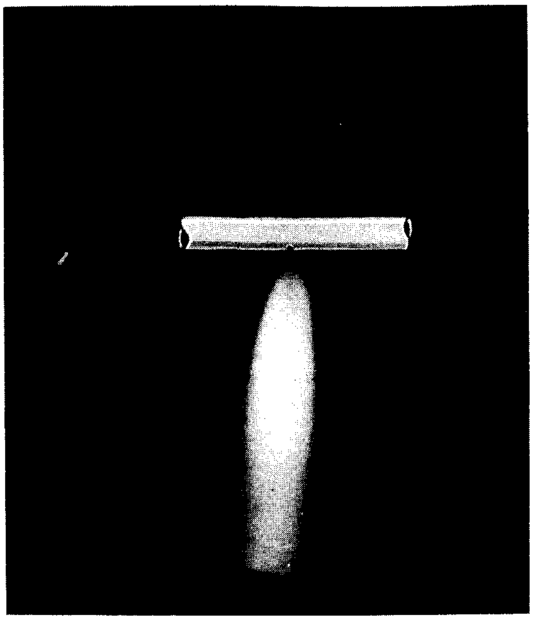


(a) Burning at high pressure.

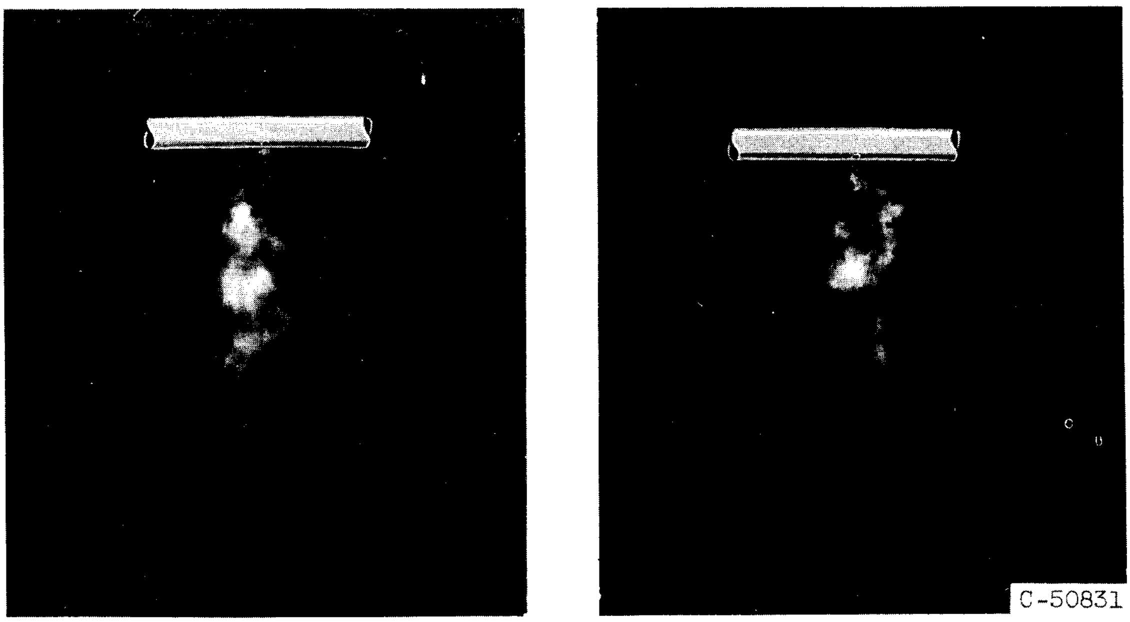


(b) Frame preceding blowoff; pressure, 0.40 atmosphere.

Figure 6. - Hydrogen diffusion flames. Orifice diameter, 0.047 inch; air static temperature, 1660° R; airflow, 241 pounds per hour; fuel flow, 1.26 pounds per hour.



(a) Time exposure.



U_a = 163 ft/sec
w_f = 0.885 lb/hr

U_a = 203 ft/sec
w_f = 0.934 lb/hr

(b) Flame at 1/1000 second. Orifice diameter, 0.042 inch; air static temperature, 2060° R; pressure, 1.05 atmospheres.

Figure 7. - Propane diffusion flames.

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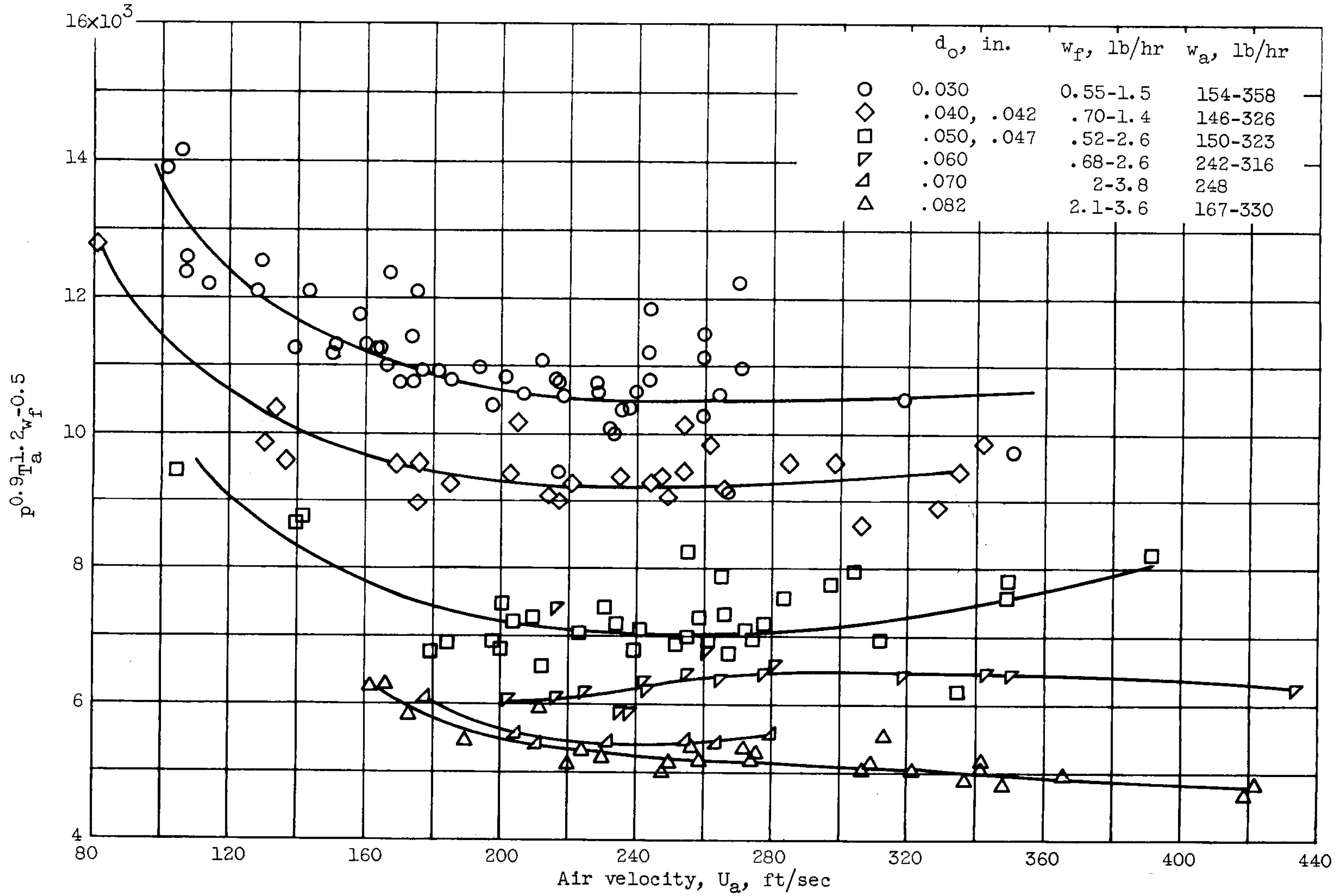
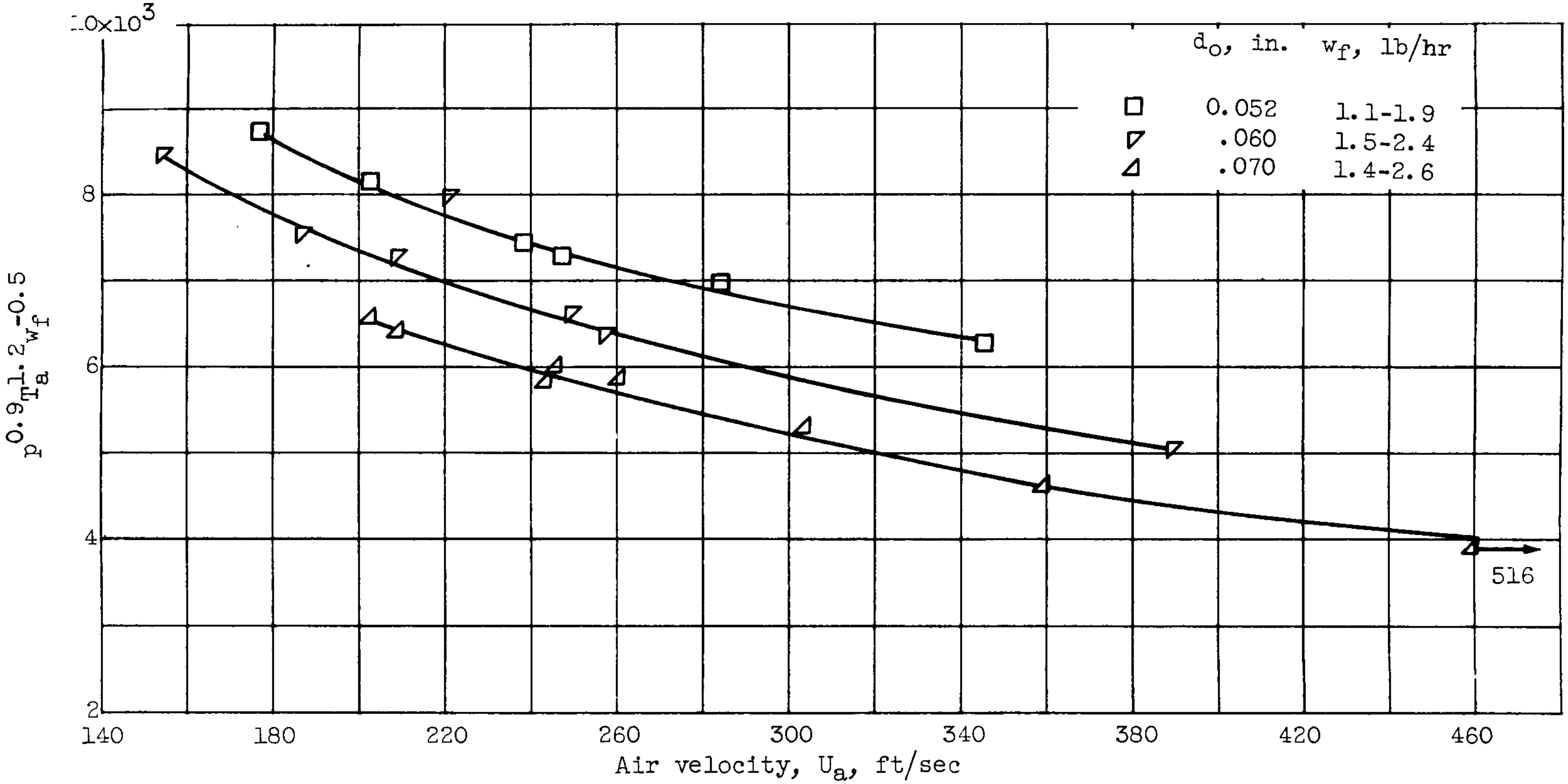


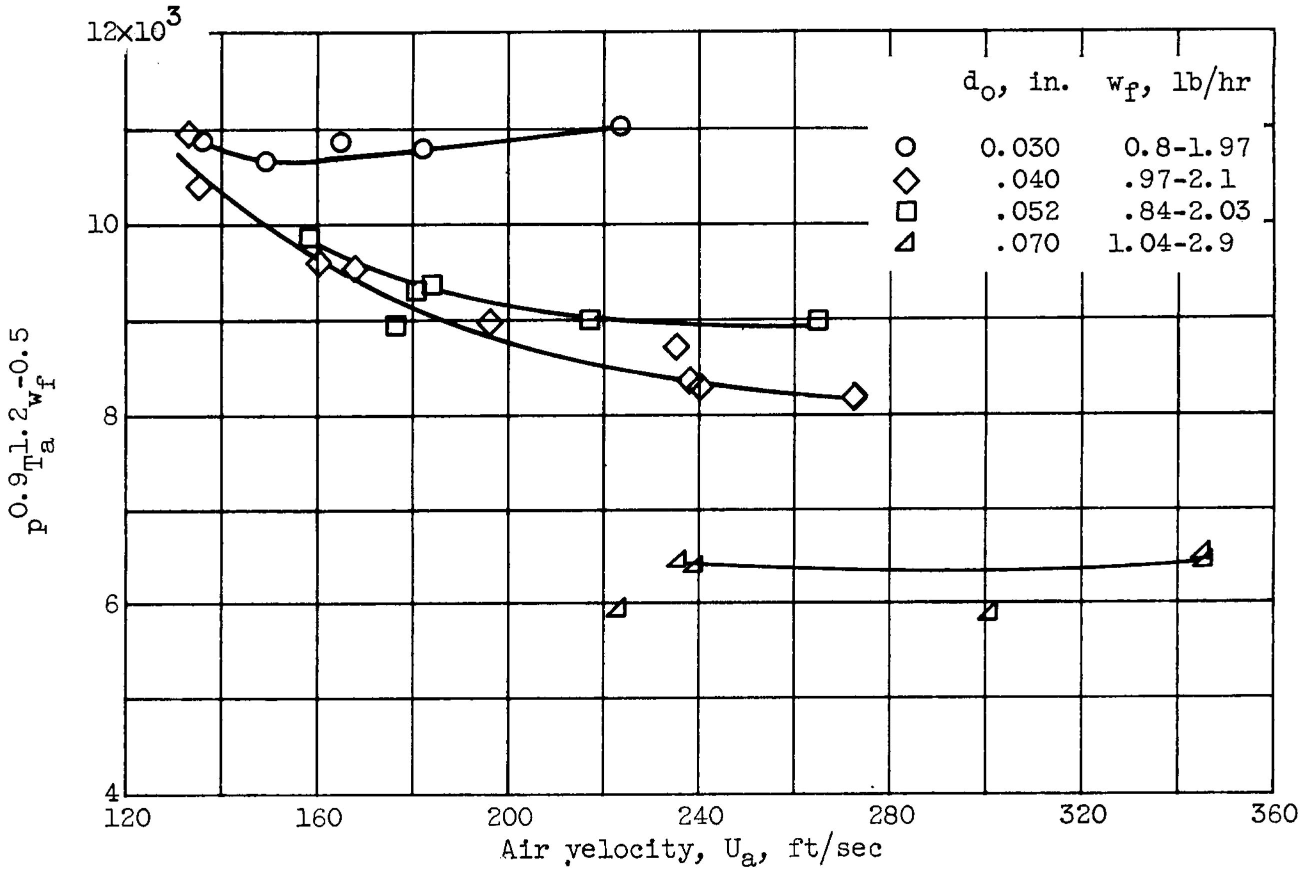
(a) Tube diameter, 0.25 inch; air static temperature, 1660° to 2160° R.

Figure 8. - Correlation of propane blowoff data.



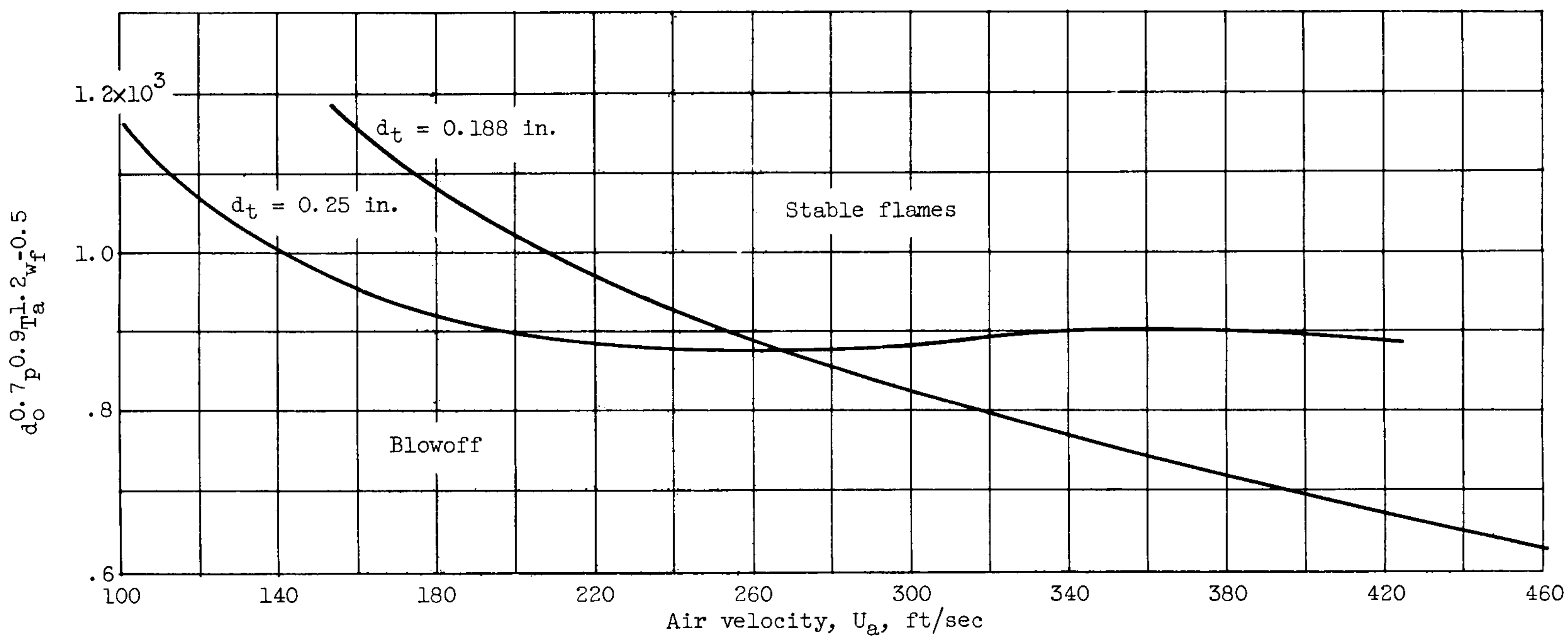
(b) Tube diameter, 0.188 inch; air static temperature, 1940° to 1970° R; airflow, 238 to 260 pounds per hour.

Figure 8. - Continued. Correlation of propane blowoff data.



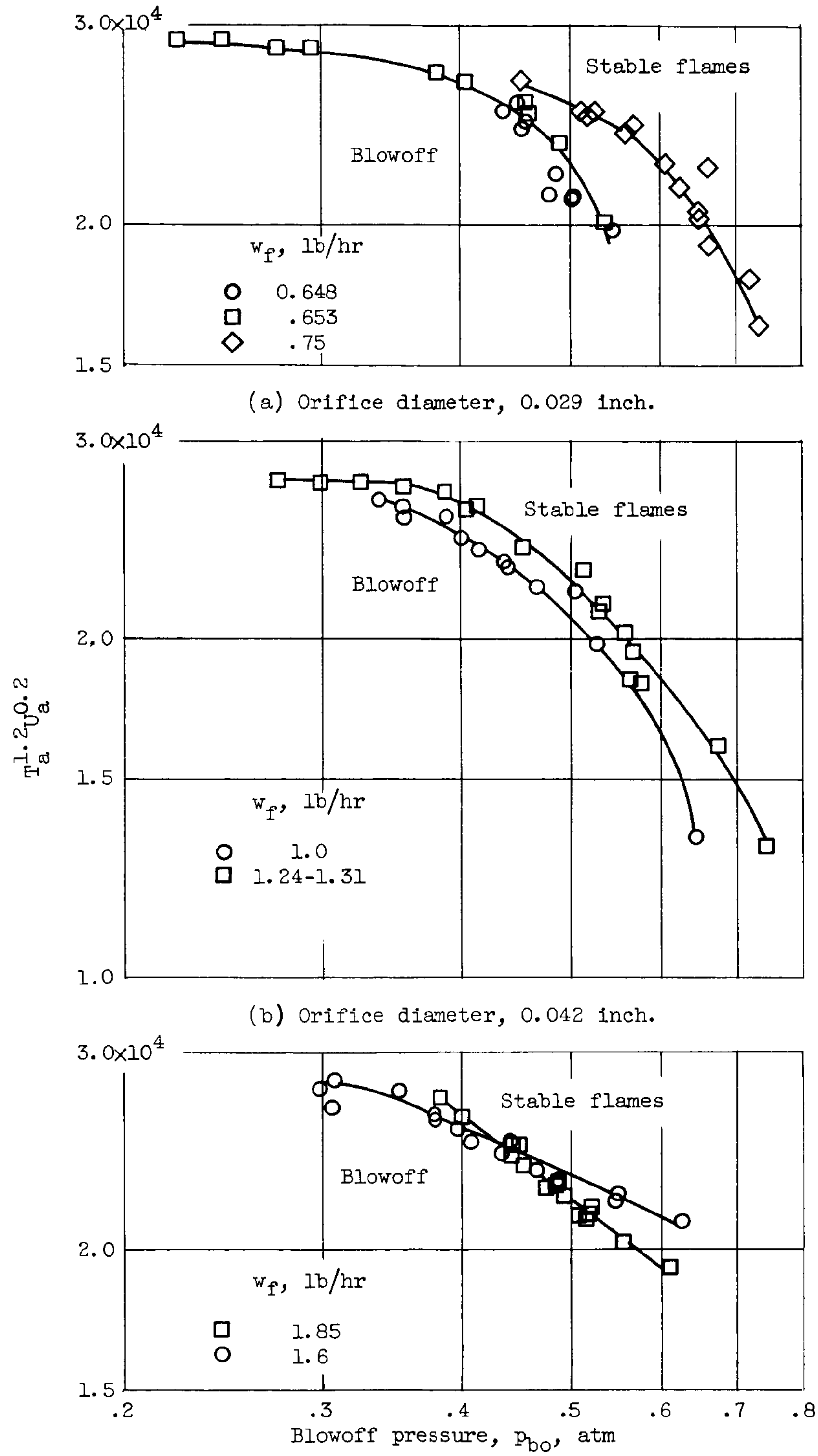
(c) Tube diameter, 0.312 inch; air static temperature, 1950° to 1990° R; airflow, 239 to 261 pounds per hour.

Figure 8. - Continued. Correlation of propane blowoff data.



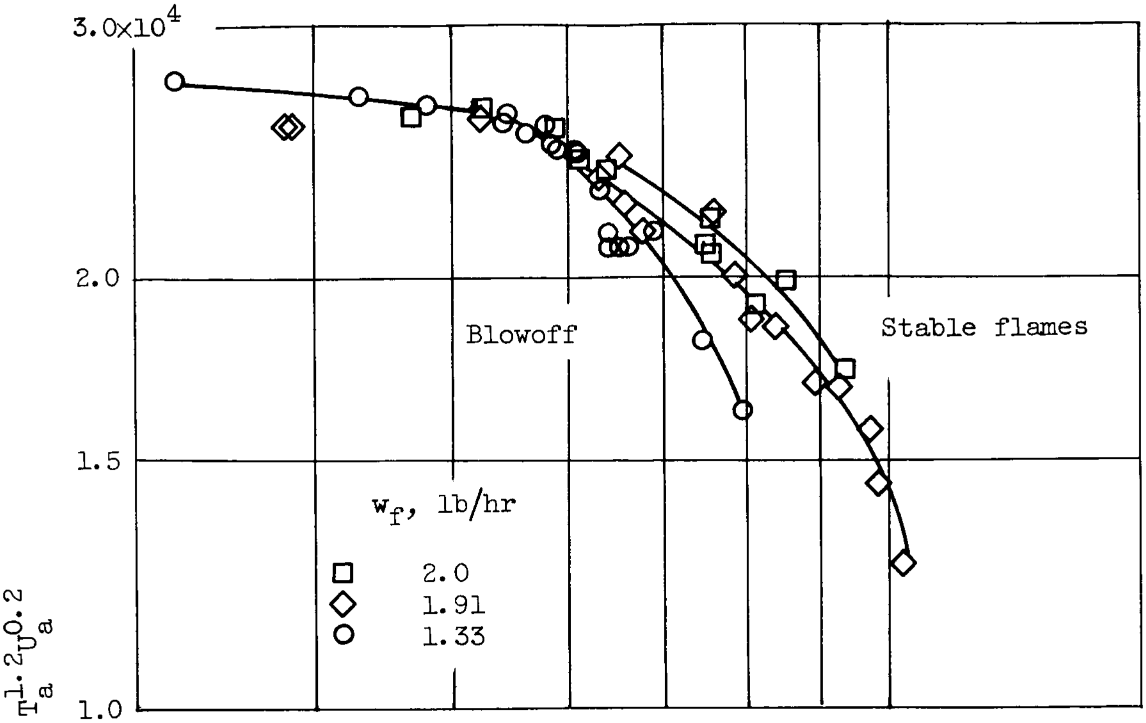
(d) Replot of figures 8(a) and (b).

Figure 8. - Concluded. Correlation of propane blowoff data.

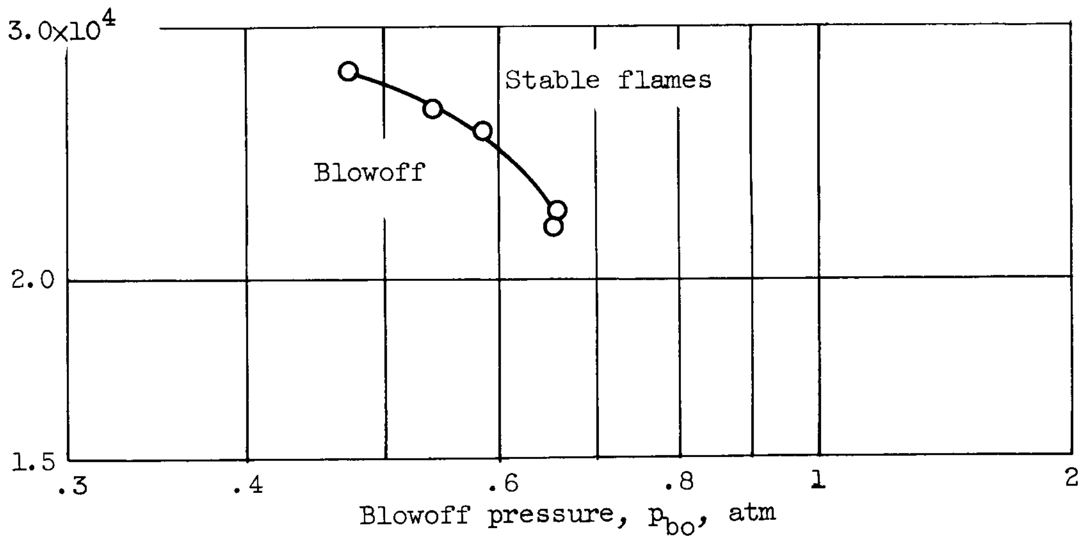


(c) Orifice diameter, 0.047 inch.

Figure 9. - Correlation of hydrogen blowoff data.



(d) Orifice diameter, 0.060 inch.



(e) Orifice diameter, 0.082 inch. Fuel flow, 3.45 pounds per hour.

Figure 9. - Concluded. Correlation of hydrogen blowoff data.